U. S. Department of Agriculture
Soil Conservation Service
Engineering Division

Technical Release No. 45
Design Unit
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TWIN CELL RECTANGULAR CONDUITS
CRITERIA AND PROCEDURES FOR STRUCTURAL DESIGN

PREFACE

This technical release is a continuation of the effort to reduce the design time required to analyze and design rectangular conduits. Two earlier technical releases, TR-42 and TR-43, deal with the design of single cell rectangular conduits. This technical release is concerned with the design of twin cell rectangular conduits.

The first chapter is important to those whose primary interest lies in obtaining and interpreting computer designs. The second chapter gives the criteria and procedures established for the structural design of these conduit cross sections. It may be useful as an indicator of approaches to the analysis and design of similar structures.

A draft of the subject technical release dated July 22, 1970, was sent to the Engineering and Watershed Planning Unit Design Engineers for their review and comment.

This technical release was prepared by Mr. Edwin S. Alling of the Design Unit, Design Branch at Hyattsville, Maryland. He also wrote the computer program.

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NOMENCLATURE

Not all nomenclature is listed. Hopefully, the meaning of any unlisted nomenclature may be ascertained from that given.

A_g ≡ gross area of column

A(i) ≡ steel area required at location i

A_s ≡ reinforcing steel area

A_{s_o} ≡ reinforcing steel area for original effective depth or original loads

A_{s_r} ≡ reinforcing steel area for reduced effective depth or reduced loads

a ≡ ratio used to obtain properties of non-prismatic, unsymmetrical members

B1 ≡ identification of first basic set of loads, those with conduit empty

b ≡ width of reinforced concrete member; ratio used to obtain properties of non-prismatic, unsymmetrical members

C_{JK} ≡ carry-over factor from end J to end K

C_{si} ≡ concentrated sidewall load for LC#i

c_{jk} ≡ carry-over coefficient

D ≡ nominal diameter of reinforcing bar

D_{ws} ≡ dead weight of sidewall

d ≡ effective depth of reinforced concrete member

d_o ≡ original effective depth

d_r ≡ reduced effective depth

d_{wb} ≡ unit dead weight on bottom slab

d_{wt} ≡ unit dead weight of top slab

E ≡ modulus of elasticity

f_c ≡ compressive stress in concrete

f_c' ≡ compressive strength of concrete

f_s ≡ allowable stress in reinforcing steel

HIGH ≡ clear height of conduit

h_c ≡ clear height of conduit

h_w ≡ internal water pressure head measured from the bottom of the top slab

I ≡ moment of inertia

L ≡ span length

LC#1 ≡ load combination number one

LC#2 ≡ load combination number two

L_b ≡ bottom slab span

L_s ≡ sidewall span

L_t ≡ top slab span

ℓ ≡ number of layers of steel

M ≡ moment

M_A ≡ design moment at A

M_{Bcse} ≡ corner moment at B for unit concentrated sidewall load, earth foundation analysis

M_{Bi} ≡ external load corner moment at B for LC#i

M_{Bhde} ≡ corner moment at B for pressure head loading, earth foundation analysis

M_{Bhye} ≡ corner moment at B for hydrostatic sidewall loading, earth foundation analysis

M^F_{Bhy} ≡ fixed end moment at B for hydrostatic sidewall loading

M_{Bube} ≡ corner moment at B for unit load on bottom slab, earth foundation analysis

M_{Buse} ≡ corner moment at B for unit load on sidewall, earth foundation analysis

M_{Bute} ≡ corner moment at B for unit load on top slab, earth foundation analysis

M_{Bt} ≡ design moment at face of the support of the top slab

M_{JK} ≡ moment at J in span JK

M^F_{JK} ≡ fixed end moment at J in span JK

m_{jk} ≡ fixed end moment coefficient

N_t ≡ direct force in top slab

P ≡ axial compressive or tensile force

PH1 ≡ horizontal unit load of LC#1

PH2 ≡ horizontal unit load of LC#2

PV1 ≡ vertical unit load of LC#1

PV2 ≡ vertical unit load of LC#2

p ≡ unit load

p_b ≡ unit load on bottom slab

p_{bi} ≡ unit load on bottom slab for LC#i

p_g ≡ gross steel ratio

p_{hd} ≡ unit load for pressure head loading

p_{hy} ≡ maximum unit load for hydrostatic sidewall loading

p_s ≡ unit load on sidewall

psf ≡ pounds per square foot

psi ≡ pounds per square inch

p_{si} ≡ unit load on sidewall for LC#i

p_t ≡ unit load on top slab

p_{ti} ≡ unit load on top slab for LC#i

R ≡ proportional reduction in loads

R_c ≡ concentrated reaction at centerwall

R_F ≡ reaction at F in half frame used for analysis

R_I ≡ reaction at I in half frame used for analysis

R_m ≡ reaction due to end moments

R_s ≡ simple beam reaction; concentrated reaction at sidewall

S(i) ≡ steel spacing required at location i

S_{JK} ≡ stiffness at end J in span JK

s ≡ spacing of reinforcing steel

s_{jk} ≡ stiffness coefficient

s_o ≡ steel spacing for original effective depth or original loads

s_r ≡ steel spacing for reduced effective depth or reduced loads

TBOT ≡ required thickness of bottom slab

TCTR ≡ required thickness of centerwall

TSBOT ≡ required thickness at bottom of sidewall

TSTOP ≡ required thickness at top of sidewall

TTOP ≡ required thickness of top slab

t ≡ thickness

t_b ≡ thickness of bottom slab

t_c ≡ thickness of centerwall

t_ℓ ≡ thickness of left support

t_r ≡ thickness of right support

t_s ≡ average thickness of sidewall

t_{sb} ≡ thickness of sidewall at the bottom

t_{st} ≡ thickness of sidewall at the top

t_t ≡ thickness of top slab

u ≡ allowable flexural bond stress in concrete

V ≡ shear

V_f ≡ shear at face of support

V_p ≡ shear at point of inflection; shear at section of maximum positive moment

v ≡ allowable shear stress in concrete

WIDE ≡ clear width of one cell of conduit

w_c ≡ clear width of one cell of conduit

x_{mid} ≡ distance from center of support to middle of clear span

x_p ≡ distance from center of support to section of maximum positive moment

γ_w ≡ unit weight of water

Δ ≡ relative translation of ends of a member

θ_J ≡ rotation at support J

ρ ≡ Δ/L

TECHNICAL RELEASE
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TWIN CELL RECTANGULAR CONDUITS
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CHAPTER 1. COMPUTER DESIGNS

Introduction

This technical release is concerned with the structural design of twin cell rectangular conduit cross sections. A computer program written in FORTRAN for IBM 360 equipment was developed to perform these designs. This technical release documents the criteria and procedures used in the computer program and explains how to obtain and interpret the computer designs.

Two previous technical releases deal with single cell rectangular conduits. These are Technical Release No. 42, "Single Cell Rectangular Conduits - Criteria and Procedures for Structural Design" and Technical Release No. 43, "Single Cell Rectangular Conduits - Catalog of Standard Designs." Material contained in TR-42 or TR-43 which is equally applicable to twin cell conduits is not fully reproduced herein. Rather than duplicate such subject matter, it is assumed the reader is familiar with these technical releases. Specific reference is made to them in some instances.

Section Designed

Figure 1-1 defines the cross sectional shape of the conduit and shows the assumed steel layout. Nomenclature adopted for the identification of computer output is indicated for the various slab thicknesses and clear spans.

The computer program determines the required thicknesses of the top and bottom slabs, the thicknesses at the top and bottom of the sidewalls, and the thickness of the centerwall. These thicknesses are the minimum possible, consistent with the selected criteria. Next the computer obtains the minimum acceptable steel areas and the maximum acceptable steel spacings at each of the twenty locations shown circled in Figure 1-1. In the case of positive, mid-span steel (positive meaning steel on the inside of the conduit) the areas actually computed are those required at the respective sections of maximum moment while the spacings computed are those required at the left and right points of inflection of the corresponding locations. The computer also determines whether or not any of the positive steel requires definite anchorage into the supports. These anchorage locations are indicated by hexagons in

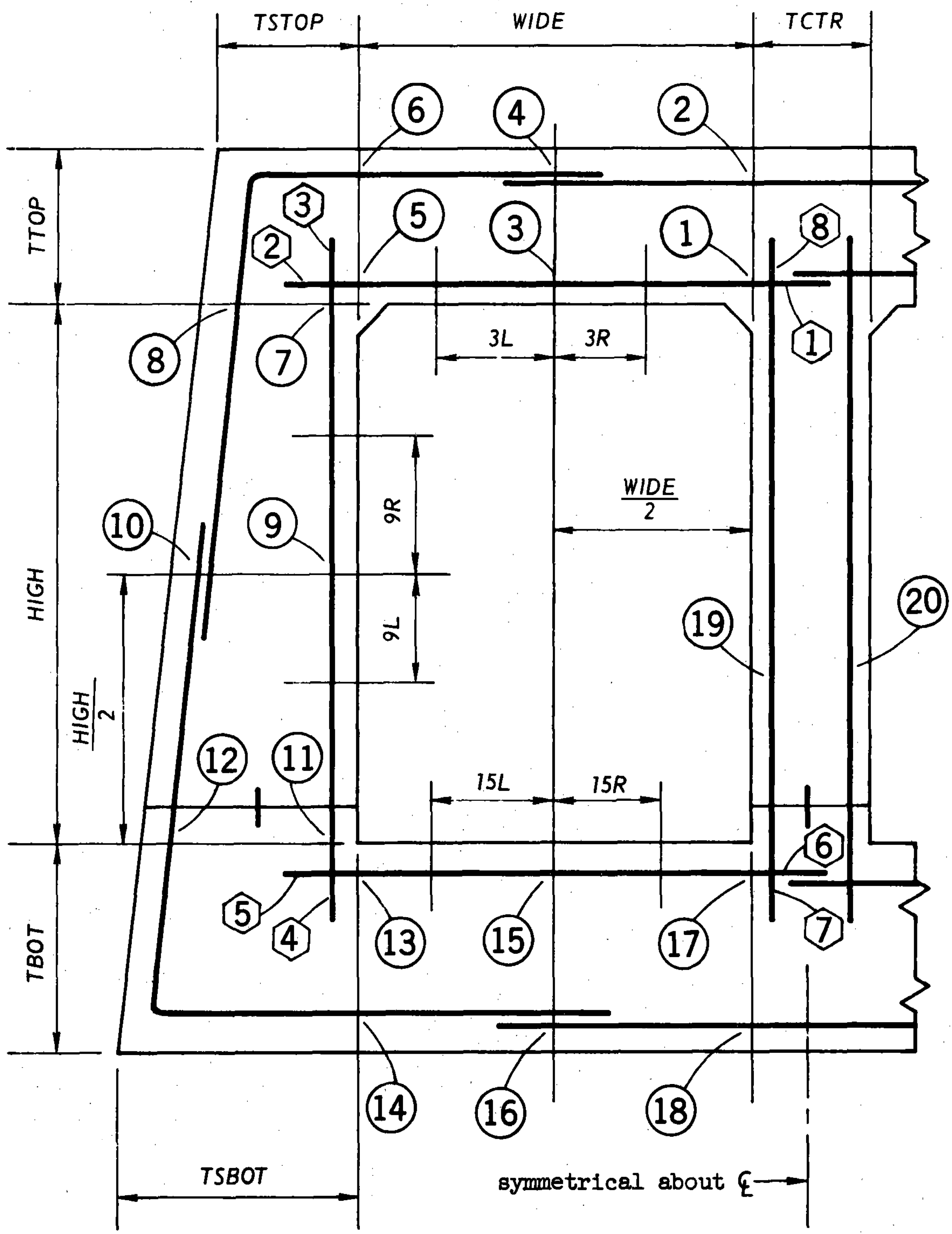

Figure 1-1. Conduit cross section and steel layout.

Figure 1-1. The computer only indicates if anchorage is needed or not needed. The designer selects the type and amount of anchorage. It may be provided by standard hooks or by embedment length if there is enough distance.

Subject to the constraint of providing at least the steel area and spacing required for the twenty locations, the designer may vary the steel layout from that shown in Figure 1-1. The best steel layout for a given design depends on the span lengths and on the amounts of steel involved.

Loads

The conduit must satisfactorily resist a number of possible loading conditions which may occur over the life of the structure. The designer must consider both initial and long term loading conditions. See pages 5-8 and the Appendix of TR-42 for a discussion of loads and load combinations for rectangular conduits.

Loads Specified by User

The design of conduit cross sections by the program is independent of the methods by which the user determines his external loads. The user specifies unit pressures in two combinations of external loads. These load combinations are defined as:

> LC#1 is the load combination having the maximum possible vertical unit load combined with the minimum horizontal unit load consistent with that vertical unit load.
>
> LC#2 is the load combination having the maximum possible horizontal unit load combined with the minimum vertical unit load consistent with that horizontal unit load.

Figure 1-2 shows the two load combinations. If PV1, PH1, PV2, and PH2 are the unit loads in psf, then by these definitions

$$PV1 \geq PV2 \text{ and } PH2 \geq PH1$$

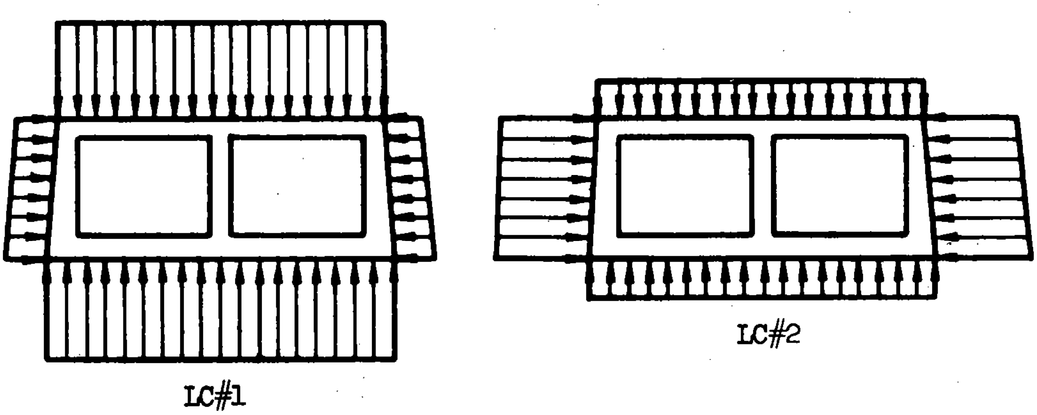

Figure 1-2. Load combinations determined by user.

Dead load should not be included in any of these unit pressures. Conduit dead weight effects are automatically considered in the program.

Loads Constructed by Program
The program constructs a number of additional loadings. These include external load combinations LC#0, LC#3, LC#4, LC#5, and LC#6 and internal water loads, all of which are discussed and defined in TR-42.

Design Mode

The program designs conduit cross sections in accordance with the design mode. A design mode characterizes the conditions for which the conduit is designed. Four modes are established:

earth foundation, no internal water load	≡ 00
earth foundation, with internal water load	≡ 01
rock foundation, no internal water load	≡ 10
rock foundation, with internal water load	≡ 11

The type of foundation assumed in the design governs the number of internal load combinations treated. LC#4, LC#5, and LC#6 are only used with rock foundations. Internal water load is included in the design of pressure conduits when it increases the requirements of the function under investigation.

Information Required to Obtain a Design

Designs of twin cell rectangular conduit cross sections may be obtained from the Design Unit at Hyattsville, Maryland. Requests should be sent to:

Head, Design Unit
Engineering Division
Soil Conservation Service
Federal Center Building
Hyattsville, Maryland 20782.

The following information is required for each design requested:

(1) the design mode,
(2) the clear height and width of one cell of the conduit,
(3) the vertical and horizontal unit loads for load combination #1, i.e., PV1 and PH1,
(4) the vertical and horizontal unit loads for load combination #2, i.e., PV2 and PH2, and
(5) any alphameric information desired by the requesting office such as site number, project number, state, and date of design.

Computer Output

The format of the output for a design is arranged so that each design is contained on a separate 8 x 10 1/2 size sheet which may readily be filed in a design folder.

Normally Completed Designs

Three example designs are shown at the end of the technical release. Special Design No. 15-TW illustrates the output for a design carried to completion. The output is identified as follows, in order of printing:

General title
Two lines of alphameric data identifying the job.
Special Design No.
Design Mode
Clear height and width of one cell, in feet.
Four loading parameters of LC#1 and LC#2, in psf.
The number of cycles of shear design and moment analysis required for the member thicknesses to converge to a stable set of thicknesses.
The number of trial designs required to obtain a design that does not require compression steel in bending.
The five slab thicknesses identified in Figure 1-1, in inches.
Concrete volume exclusive of any fillets at the top corners of the conduit in cubic yards per foot of conduit.
Steel area required at location 1 identified in Figure 1-1, in square inches per foot.
Steel spacing required at location 1 identified in Figure 1-1, in inches.
Steel area and spacing required at the remaining 19 locations.
Distances from mid-span locations 3, 9, and 15 to the corresponding left and right points of inflection, in feet.
Code indicating the positive steel that requires definite anchorage into the corners of the conduit, for example 02005600 means anchorage is required at anchorage locations 2, 5, and 6, but not at anchorage locations 1, 3, 4, 7, and 8.

Deleted Designs

In certain cases the design of a cross section is not completed. If a design is not completed, the output contains reference to a message giving the reason the design was deleted. These "Design Deleted Messages" are listed below. At least one set of slab thicknesses is given when a design is deleted. The thicknesses given with any of messages 1-4 are the thicknesses at the time the design was terminated. They are given for information only and are not acceptable values for subsequent design.

Message No. 1:
A stable set of member thicknesses was not obtained in 99 cycles of shear design and moment analysis.

Message No. 2:
The top slab required effective depth for shear exceeds the clear cell width of the conduit. The shear criteria is considered invalid.

Message No. 3:
The sidewall required effective depth for shear exceeds the clear height of the conduit. The shear criteria is considered invalid.

Message No. 4:
The bottom slab required effective depth for shear exceeds the clear cell width of the conduit. The shear criteria is considered invalid.

Message No. 5:
The required thickness of one of the slabs exceeds 48 inches. This is set arbitrarily as the maximum acceptable thickness. The thicknesses of the last trial design are given first, the thicknesses as originally required by shear are given next.

Message No. 6:
Ten trial designs have been made. If the thicknesses of the last trial design were used, compression steel would be required in the top slab. Thicknesses of the last trial design are given first, thicknesses as originally required by shear are given next.

Message No. 7:
Ten trial designs have been made. If the thicknesses of the last trial design were used, compression steel would be required in the sidewalls. Thicknesses of the last trial design are given first, thicknesses as originally required by shear are given next.

Message No. 8:
Ten trial designs have been made. If the thicknesses of the last trial design were used, compression steel would be required in the bottom slab. Thicknesses of the last trial design are given first, thicknesses as originally required by shear are given next.

Special Design Nos. 16-TW and 17-TW, at the end of the technical release, illustrate the output for designs that are deleted. A design is deleted by the condition first encountered. Thus 16-TW would have been deleted for excessive thickness if it had not been deleted for invalid shear criteria.

Possible Modifications to a Computer Design

After a design has been obtained, it may be desirable to modify the computed steel requirements of the cross section. See pages 8 - 10 of TR-43 for development of this concept. As given therein, for a proportional reduction of all loads:

$$s_r = s_o(1/R)$$

and

$$A_{s_r} = A_{s_o}(R)$$

where

s_r = bar spacing for reduced loads

s_o = bar spacing for original loads

R = proportional reduction in loads

A_{s_r} = steel area for reduced loads

A_{s_o} = steel area for original loads

Also, as given in TR-43, with the introduction of multiple layers of steel:

$$s_r = s_o \ell \left(\frac{d_r}{d_o}\right)$$

and

$$A_{s_r} = \frac{A_{s_o}}{\ell}\left(\frac{d_o}{d_r}\right)^2$$

where

s_r = bar spacing per layer for reduced effective depth

s_o = bar spacing for original effective depth

ℓ = number of layers of steel

d_r = reduced effective depth

d_o = original effective depth

A_{s_r} = steel area per layer for reduced effective depth

A_{s_o} = steel area for original effective depth

In no case should spacings be increased to more than 18 inches nor areas be reduced to less than that required by temperature and shrinkage.

CHAPTER 2. CRITERIA AND PROCEDURES

Design Thicknesses and Spans

Figure 1-1 defines the conduit cross section and identifies computer output nomenclature. Figure 2-1 defines nomenclature for design purposes.

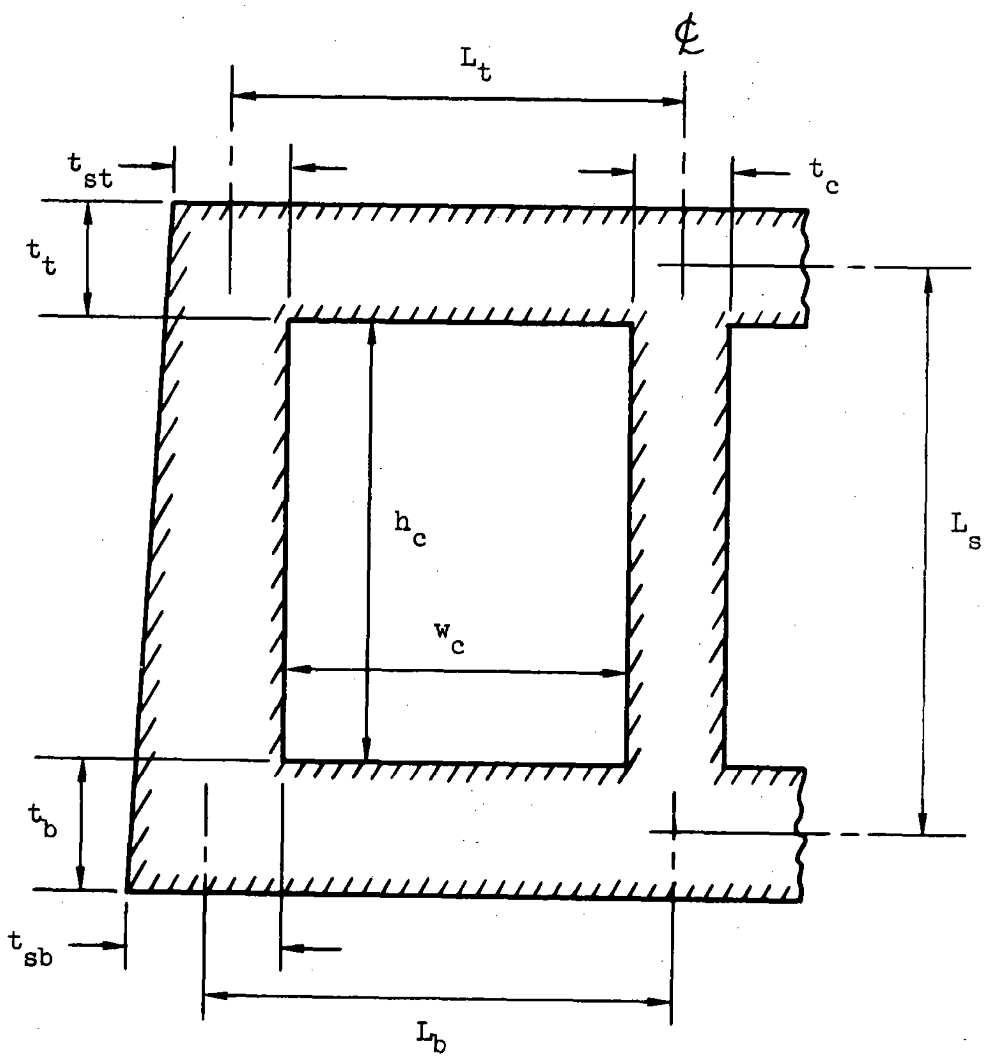

Figure 2-1. Conduit spans and member thicknesses.

In following analyses, take

$$L_t = w_c + \frac{1}{2}(t_{st} + t_c)$$

$$L_s = h_c + \frac{1}{2}(t_t + t_b)$$

$$L_b = w_c + \frac{1}{2}(t_{sb} + t_c)$$

For the sidewall thickness, in stiffness calculations, take

$$t_s = \frac{1}{2}(t_{st} + t_{sb})$$

Analyses for Indeterminate Moments

General Considerations

Slope Deflection is selected as the method of analysis for this work. Utilizing vertical symmetry, the closed twin cell rectangular shape is indeterminate to the third degree for conduits on earth foundations or to the fourth degree for conduits on rock foundations. Use of Slope Deflection, which is a stiffness method, alters the problem to the determination of three displacements for conduits on earth or to two displacements for conduits on rock. Members are assumed non-prismatic and unsymmetrical. The moment of inertia is constant within the clear span and is assumed infinite outside the clear span.

Elastic Constants

Figure 2-2 shows a typical member and the assumed variation in moments of inertia.

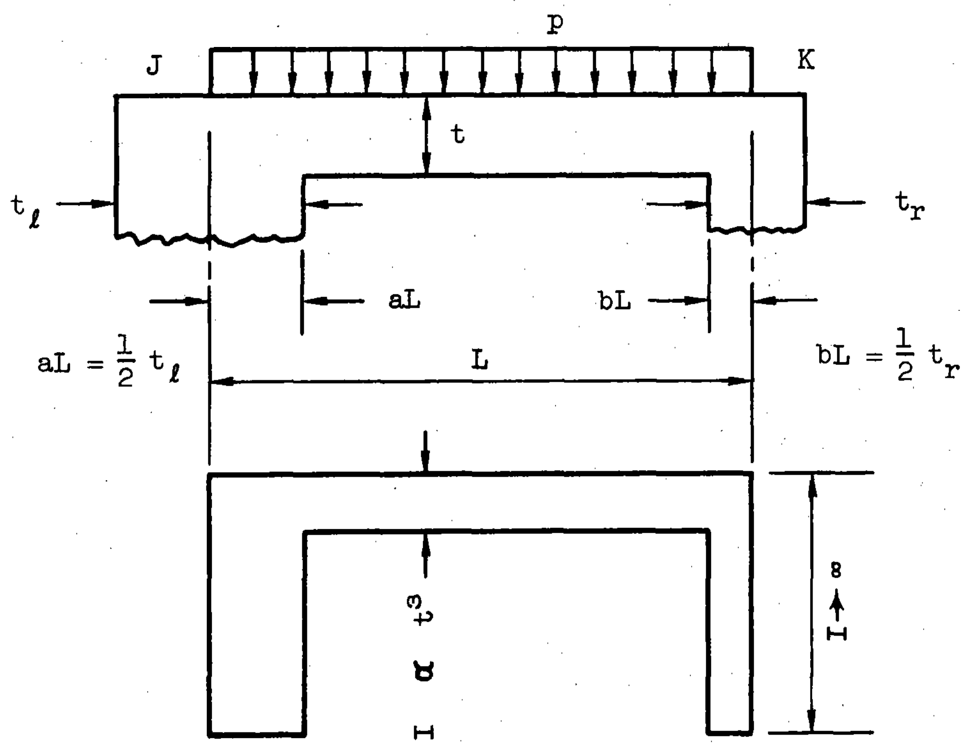

Figure 2-2. Typical member and variation in moment of inertia.

Carry over factors, stiffnesses, and fixed end moments for uniform load may be computed from the relations:

$$C_{JK} = c_{jk}$$
$$C_{KJ} = c_{kj}$$
$$S_{JK} = s_{jk}EI/L \quad \alpha \quad s_{jk}t^3/L$$
$$S_{KJ} = s_{kj}EI/L \quad \alpha \quad s_{kj}t^3/L$$
$$M^F_{JK} = m_{jk}\ pL^2$$
$$M^F_{KJ} = m_{kj}\ pL^2$$

where

C_{JK} is the carry over factor from end J to end K

C_{KJ} is the carry over factor from end K to end J

S_{KJ} is the stiffness at end K in span JK

S_{JK} is the stiffness at end J in span JK

M^F_{JK} is the fixed end moment at J in span JK

M^F_{KJ} is the fixed end moment at K in span JK

The jk subscripted coefficients may be computed from the expressions

$$c_{jk} = \frac{3}{(2 + a - 2b)\left\{\frac{(1 - a - b)}{(1 + a - b)}\right\} + 3a} - 1$$

$$s_{jk} = \frac{1}{(1 - a - b)\left\{1 - 0.5(1 + a - b)(1 + c_{jk})\right\}}$$

$$m_{jk} = \frac{1}{12}\left\{(1 - a - b)^2 + 6a(1 - b)\right\}$$

The kj subscripted coefficients may be computed from the same expressions by interchanging subscripts and values of a and b.

Moments Due to End Translation Without Rotation

As discussed below, when conduits are founded on earth, relative translation of the ends of the top and bottom slabs can occur. Derivation of expressions for the fixed end moments caused by such movements is assisted by Figure 2-3.

In Figure 2-3, sketch (a) shows a member with a relative end translation of Δ but with no rotation of the ends. Sketch (b) shows a simply supported member with the same end translation. Sketches (c) and (d) show the moments required to produce zero rotation at each end.

Thus

$$M_{JK} = (S_{JK} + C_{KJ}S_{KJ})\rho$$
$$M_{KJ} = (S_{KJ} + C_{JK}S_{JK})\rho$$

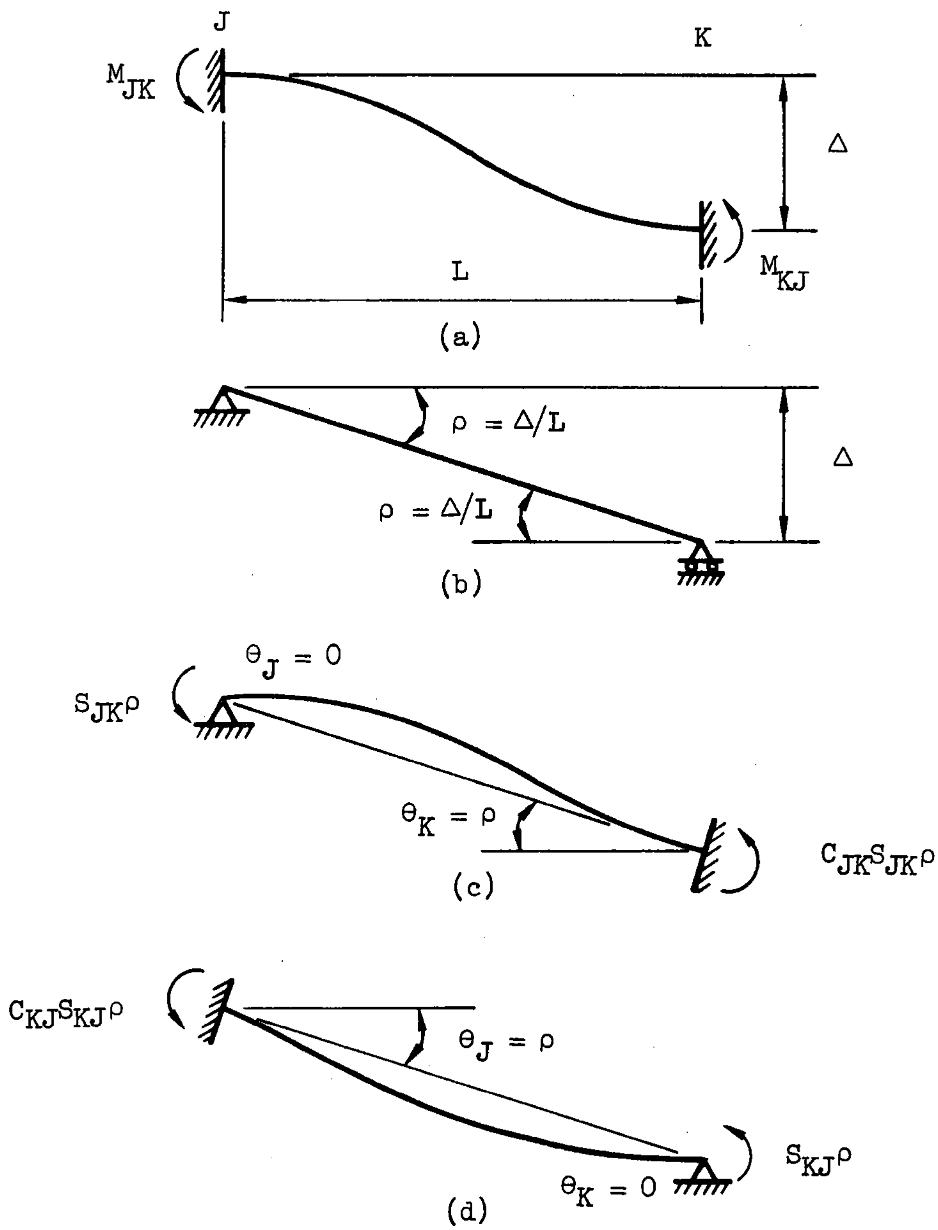

Figure 2-3. Moments due to relative end translation.

General Slope Deflection Equation

The Slope Deflection Equation used in this analysis is derived for the general case of members subjected to applied loads, end rotations, and relative end translations.

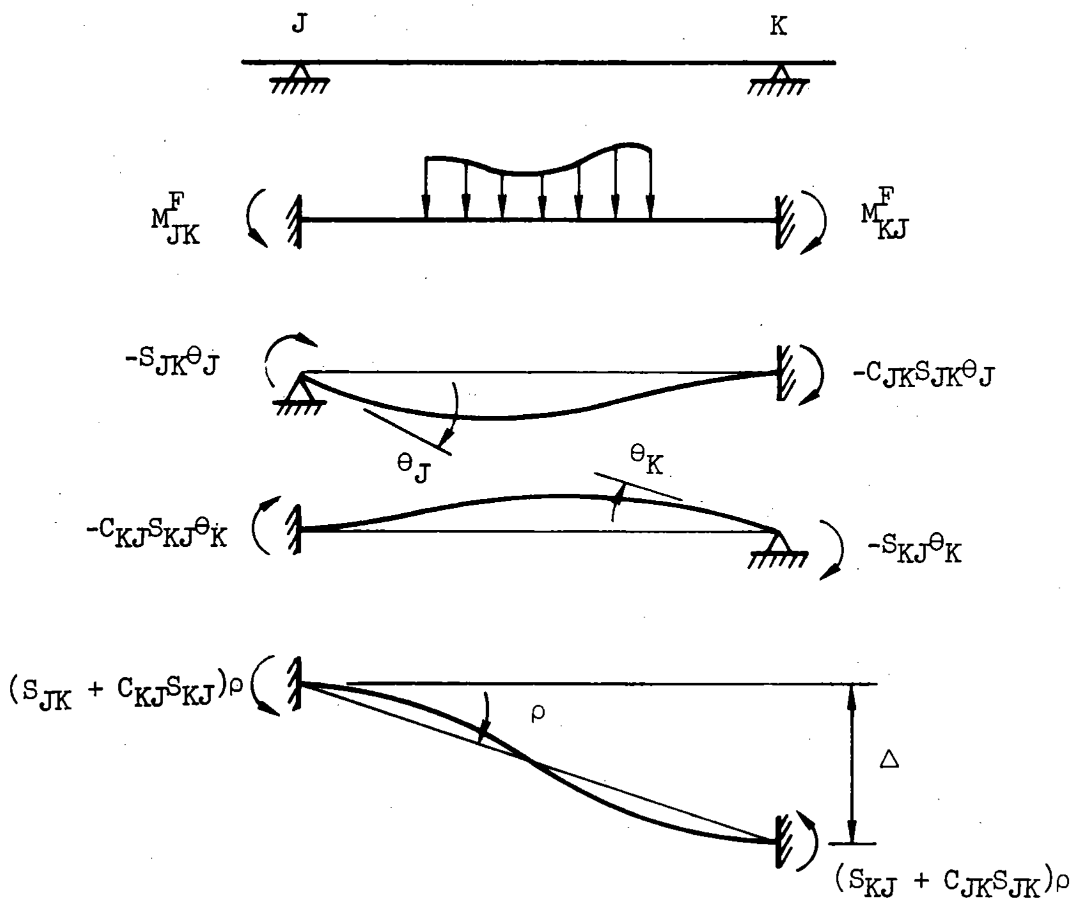

Figure 2-4. Development of Slope Deflection equation.

The usual Slope Deflection sign convention is followed; clockwise rotations are positive, clockwise joint moments are positive. From Figure 2-4

$$M_{JK} = M^F_{JK} - S_{JK}\,\theta_J - C_{KJ}S_{KJ}\theta_K + (S_{JK} + C_{KJ}S_{KJ})\rho$$

and

$$M_{KJ} = M^F_{KJ} - S_{KJ}\theta_K - C_{JK}S_{JK}\theta_J + (S_{KJ} + C_{JK}S_{JK})\rho$$

where

M_{JK} is the moment at J in JK

M_{KJ} is the moment at K in JK

θ_J is the end rotation at J in JK

θ_K is the end rotation at K in JK

Δ is the relative translation of ends J and K in JK

$\rho = \Delta/L$

Slope Deflection Method
Both the loading on, and the shape of, these twin cell rectangular conduits are symmetrical about the vertical centerline of the structure. Hence no joint translates horizontally. There is no horizontal axis of symmetry of the structure. Hence there will be relative vertical translation of the sidewalls and the centerwall unless it is prevented.

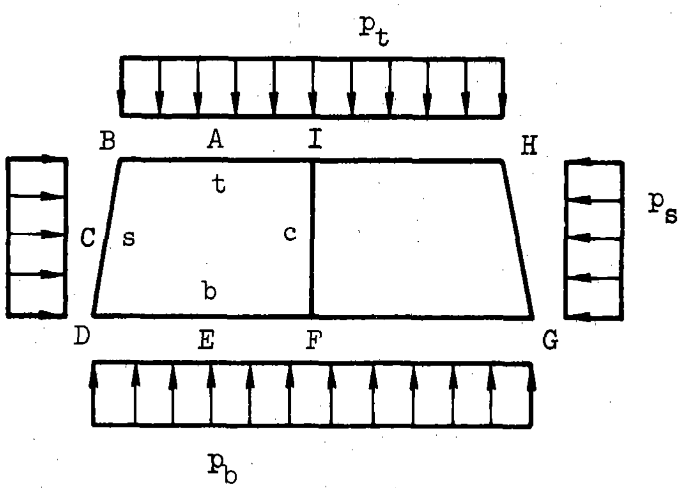

Figure 2-5. Designations for analyses.

By vertical symmetry $\theta_I = \theta_F = 0$, $\theta_H = -\theta_B$, and $\theta_G = -\theta_D$. Thus only half the structure need be included in the analysis and joints I and F can be treated as fixed.

Conduits on earth foundations. - When the conduit is founded on earth, the loading on the bottom slab is assumed uniformly distributed and relative vertical translation is not prevented. Sketch (a) of Figure 2-6

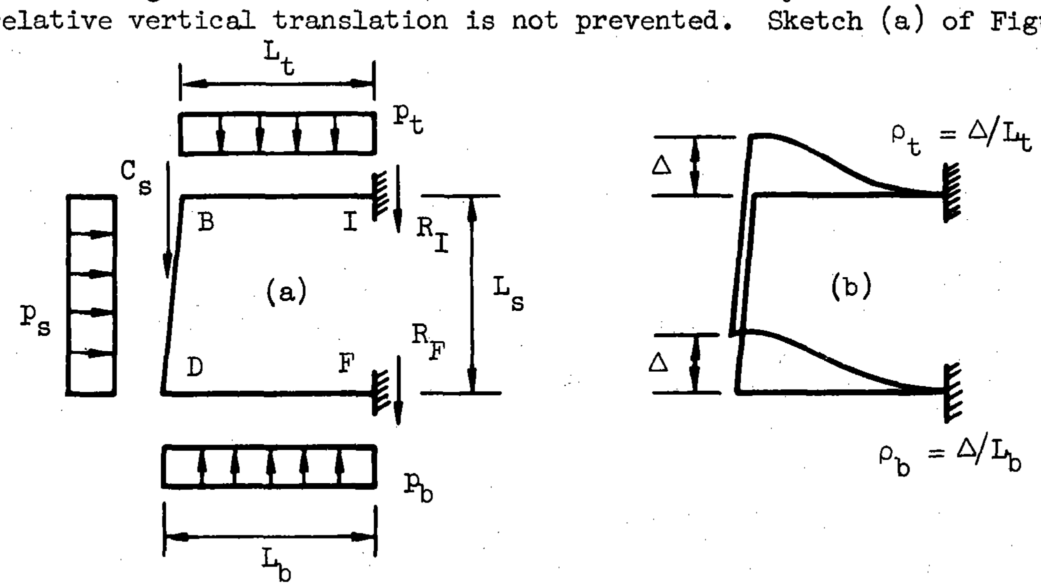

Figure 2-6. Analysis for conduits founded on earth.

shows the general loading on the half frame and sketch (b) shows the displacement diagram caused by the relative translation of the ends of the top and bottom slabs. The concentrated load, C_s, shown acting on the sidewall is due to the dead weight of the sidewall and to the vertical external load acting on the sidewall. A similar concentrated load exists on the sidewall of single cell conduits but causes no bending since there is no relative vertical translation.

There are three unknown displacements, they are the two rotations θ_B and θ_D, and the translation Δ. Three statical equations are required, these are the two joint equations

$$\Sigma M_B = 0$$

$$\Sigma M_D = 0$$

and the shear equation

$$\Sigma V = 0$$

Substituting moment and load values into the statical equations, obtain

$$M_{BI} + M_{BD} = 0$$

$$M_{DB} + M_{DF} = 0$$

and

$$R_I + R_F = p_b L_b - p_t L_t - C_s$$

or

$$\frac{M_{BI} + M_{IB}}{L_t} - \frac{1}{2} p_t L_t + \frac{M_{DF} + M_{FD}}{L_b} + \frac{1}{2} p_b L_b = p_b L_b - p_t L_t - C_s$$

rearranging

$$\frac{M_{BI} + M_{IB}}{L_t} + \frac{M_{DF} + M_{FD}}{L_b} = \frac{1}{2} p_b L_b - \frac{1}{2} p_t L_t - C_s$$

Repeated application of the Slope Deflection equations results in the moment expressions

$$M_{IB} = M^F_{IB} - C_{BI} S_{BI} \theta_B + (S_{IB} + C_{BI} S_{BI}) \Delta/L_t$$

$$M_{BI} = M^F_{BI} - S_{BI} \theta_B + (S_{BI} + C_{IB} S_{IB}) \Delta/L_t$$

$$M_{BD} = M^F_{BD} - S_{BD} \theta_B - C_{DB} S_{DB} \theta_D$$

$$M_{DB} = M^F_{DB} - S_{DB} \theta_D - C_{BD} S_{BD} \theta_B$$

$$M_{DF} = M^F_{DF} - S_{DF} \theta_D + (S_{DF} + C_{FD} S_{FD}) \Delta/L_b$$

$$M_{FD} = M^F_{FD} - C_{DF} S_{DF} \theta_D + (S_{FD} + C_{DF} S_{DF}) \Delta/L_b$$

Substitution of these moment expressions into the statical equations and simplifying, yields the three displacement equations

$$(S_{BI} + S_{BD})\theta_B \quad + \quad (C_{DB}S_{DB})\theta_D - \frac{1}{L_t}(S_{BI} + C_{IB}S_{IB})\Delta = M^F_{BI} + M^F_{BD}$$

$$(C_{DB}S_{DB})\theta_B \quad + \quad (S_{DB} + S_{DF})\theta_D - \frac{1}{L_b}(S_{DF} + C_{FD}S_{FD})\Delta = M^F_{DB} + M^F_{DF}$$

$$- \frac{1}{L_t}(S_{BI} + C_{IB}S_{IB})\theta_B - \frac{1}{L_b}(S_{DF} + C_{FD}S_{FD})\theta_D$$

$$+ \left\{\frac{1}{L_t^2}(S_{BI} + S_{IB} + 2C_{IB}S_{IB}) + \frac{1}{L_b^2}(S_{DF} + S_{FD} + 2C_{FD}S_{FD})\right\}\Delta$$

$$= \frac{1}{2} p_b L_b - \frac{1}{2} p_t L_t - C_s - \frac{M^F_{DF} + M^F_{FD}}{L_b} - \frac{M^F_{BI} + M^F_{IB}}{L_t}$$

For a specific load situation, the displacements θ_B, θ_D, and Δ may be determined from the above non-homogeneous linear equations by any of several methods. The values of the displacements can then be inserted in the Slope Deflection equations to determine end moments. In this work, the moments M_{IB}, M_{BI}, M_{DF}, and M_{FD} are evaluated.

Conduits on rock foundations. - When the conduit is analyzed for rock foundations, the external loading on the bottom of the conduit is assumed concentrated at the sidewalls and centerwall. The bottom slab itself is not loaded. Figure 2-7 shows the assumed loading. If relative vertical translation is not prevented, the R loads can have any

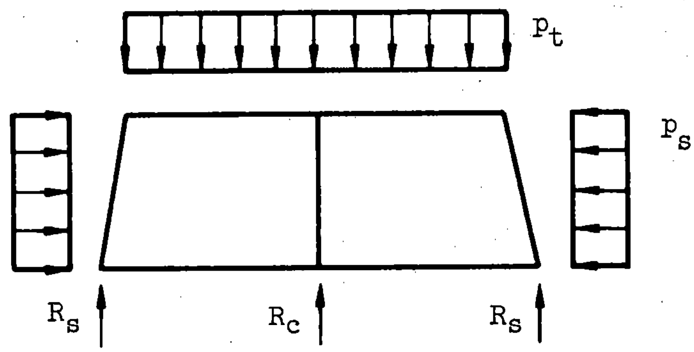

Figure 2-7. Conduit on rock.

arbitrary values so long as $\Sigma V = 0$. The associated translation is determinable. If relative vertical translation is prevented, the R loads have unique values. When conduits are analyzed for rock foundations, it is assumed that relative translation is essentially prevented. Figure 2-8 shows the half frame in which the sidewall is not free to translate.

There are two unknown displacements, they are the two rotations θ_B and θ_D. Two statical equations are required, these are

$$\Sigma M_B = M_{BI} + M_{BD} = 0$$

$$\Sigma M_D = M_{DB} + M_{DF} = 0$$

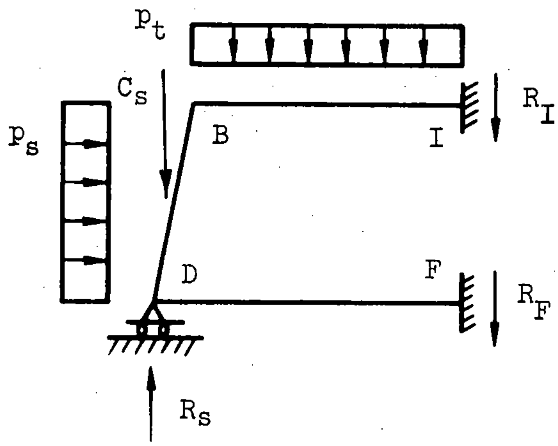

Figure 2-8. Analysis for conduits founded on rock.

The Slope Deflection equations give

$$M_{IB} = M^F_{IB} - C_{BI}S_{BI}\theta_B$$

$$M_{BI} = M^F_{BI} - S_{BI}\theta_B$$

$$M_{BD} = M^F_{BD} - S_{BD}\theta_B - C_{DB}S_{DB}\theta_D$$

$$M_{DB} = M^F_{DB} - S_{DB}\theta_D - C_{BD}S_{BD}\theta_B$$

$$M_{DF} = M^F_{DF} - S_{DF}\theta_D$$

$$M_{FD} = M^F_{FD} - C_{DF}S_{DF}\theta_D$$

Substitution of these moment expressions into the statical equations yields the two displacement equations

$$(S_{BI} + S_{BD})\theta_B + (C_{DB}S_{DB})\theta_D = M^F_{BI} + M^F_{BD}$$

$$(C_{DB}S_{DB})\theta_B + (S_{DB} + S_{DF})\theta_D = M^F_{DB} + M^F_{DF}$$

The values of the displacements θ_B and θ_D may be determined from the above equations and then inserted in the Slope Deflection equations to determine desired end moments. Note that the reaction R_s is not evaluated in this analysis and that the concentrated sidewall load C_s causes no bending since the sidewall does not translate vertically.

Analyses of Corner Moments

For a particular set of slab thicknesses, indeterminate analyses for moments can be performed. Before this is done, the unit loads on the top, sides, and bottom slabs are evaluated for the seven external load combinations previously established. These are

$$\left.\begin{aligned} p_{ti} &= PVN + d_{wt} \\ p_{si} &= PHN \\ p_{bi} &= PVN + d_{wb} \\ \text{or} \quad & \\ p_{bi} &= 0 \end{aligned}\right\} \quad \begin{aligned} N &= 1 \text{ or } 2 \\ i &= 0, 1, 2, 3, 4, 5, 6 \end{aligned}$$

in which

$$d_{wt} = 150\ t_t/12$$

$$d_{wb} = \frac{150\{w_c t_t + (h_c + (t_t + t_b)/12)(t_{sb} + t_{st} + t_c)/2\}/12}{w_c + (t_{sb} + t_c/2)/12}$$

The concentrated sidewall load for conduits on earth, is given by

$$C_{si} = (PVN)(t_{sb} - t_{st})/24 + D_{ws} \left\} \begin{aligned} N &= 1 \text{ or } 2 \\ i &= 0, 1, 2, 3 \end{aligned}\right.$$

the dead weight is taken as

$$D_{ws} = 150\{(h_c + (t_t + t_b)/12)(t_{sb} + t_{st})/2 - (t_{st}t_t + t_{sb}t_b)/24\}/12$$

In the above expressions, thicknesses are in inches, spans are in feet, and

d_{wt} = dead wt of top slab, in psf

d_{wb} = dead wt on bottom slab, in psf

D_{ws} = dead wt of sidewall, in plf

C_{si} = concentrated sidewall load for LC#i, in plf

p_{ti} = unit load on top slab for LC#i, in psf

psi = unit load on sidewall for LC#i, in psf

p_{bi} = unit load on bottom slab for LC#i, in psf

Unit Load Analyses

For convenience, the corner moments for external load combinations and for internal pressure head loading are obtained from unit load analyses. The loadings needed are shown in Figure 2-9.

Analyses are performed for these unit loads, for both earth and rock foundation cases. However, as previously indicated, C_s is used only with earth foundations. The moments M_{BI}, M_{IB}, M_{DF} and M_{FD} for a unit load on the top slab, in ft-lbs per lb of loading, are designated M_{Bute}, M_{Iute}, M_{Dute}, and M_{Fute} for earth foundation analyses and M_{Butr}, M_{Iutr}, M_{Dutr}, and M_{Futr} for rock foundation analyses. Similar

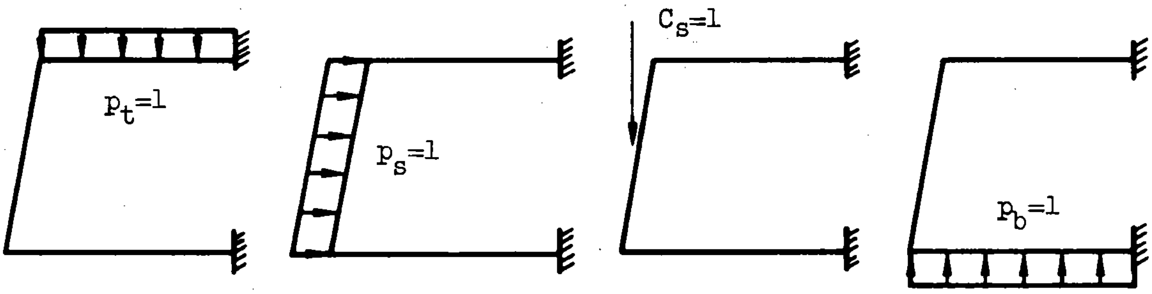

Figure 2-9. Loadings for unit load analyses.

moment designations are made for unit load on the sidewall, unit concentrated sidewall load, and unit load on the bottom slab. The subscripts us, cs, and ub respectively, are substituted for the subscripts ut.

External Load Corner Moments

Corner moments for a given load combination may be obtained as the sums of the respective unit load moments times the corresponding actual external loads. The nomenclature $M_{Bi} = M_{BIi}$, $M_{Ii} = M_{IBi}$, $M_{Di} = M_{DFi}$, and $M_{Fi} = M_{FDi}$ is adopted and Slope Deflection signs are preserved. Thus, for earth foundation analyses:

$$\left.\begin{aligned} M_{Bi} &= p_{ti}M_{Bute} + p_{si}M_{Buse} + p_{bi}M_{Bube} + C_{si}M_{Bcse} \\ M_{Ii} &= p_{ti}M_{Iute} + p_{si}M_{Iuse} + p_{bi}M_{Iube} + C_{si}M_{Icse} \\ M_{Di} &= p_{ti}M_{Dute} + p_{si}M_{Duse} + p_{bi}M_{Dube} + C_{si}M_{Dcse} \\ M_{Fi} &= p_{ti}M_{Fute} + p_{si}M_{Fuse} + p_{bi}M_{Fube} + C_{si}M_{Fcse} \end{aligned}\right\} \quad i = 0, 1, 2, 3$$

For rock foundation analyses:

$$\left.\begin{aligned} M_{Bi} &= p_{ti}M_{Butr} + p_{si}M_{Busr} \\ M_{Ii} &= p_{ti}M_{Iutr} + p_{si}M_{Iusr} \\ M_{Di} &= p_{ti}M_{Dutr} + p_{si}M_{Dusr} \\ M_{Fi} &= p_{ti}M_{Futr} + p_{si}M_{Fusr} \end{aligned}\right\} \quad i = 4, 5, 6$$

For reasons discussed on page 28 of TR-42, that is, $t_{sb} > t_{st}$ and sidewall loading is actually trapezoidal, a second set of corner moments is computed in which the moments due to side loads are arbitrarily decreased 10 percent for M_{Bi} and M_{Ii} and increased 10 percent for M_{Di} and M_{Fi}. This second set of external load corner moments is used only in those instances when it is conservative to take lower moments at B and I or higher moments at D and F.

Analyses for Internal Water Loads

Moments due to pressure head loading may be computed using the unit load analyses. For earth foundation analyses

$$M_{Bhde} = -p_{hd}(M_{Bute} + M_{Buse} + M_{Bube})$$
$$M_{Ihde} = -p_{hd}(M_{Iute} + M_{Iuse} + M_{Iube})$$

$$M_{Dhde} = -p_{hd}(M_{Dute} + M_{Duse} + M_{Dube})$$
$$M_{Fhde} = -p_{hd}(M_{Fute} + M_{Fuse} + M_{Fube})$$

For rock foundation analyses

$$M_{Bhdr} = -p_{hd}(M_{Butr} + M_{Busr} + M_{Bubr})$$
$$M_{Ihdr} = -p_{hd}(M_{Iutr} + M_{Iusr} + M_{Iubr})$$
$$M_{Dhdr} = -p_{hd}(M_{Dutr} + M_{Dusr} + M_{Dubr})$$
$$M_{Fhdr} = -p_{hd}(M_{Futr} + M_{Fusr} + M_{Fubr})$$

The minus signs are used since p_{hd} is an outward acting load.

Moments due to hydrostatic sidewall loading may be computed for earth and rock foundation cases after the fixed end moments are obtained. From page 29 of TR-42, the fixed end moments are

$$M^F_{Bhy} = +(\frac{1}{30}\, p_{hy}\, h_c{}^2 + \frac{1}{160}\, p_{hy}\, h_c\, t_t)$$
$$M^F_{Dhy} = -(\frac{1}{20}\, p_{hy}\, h_c{}^2 + \frac{7}{480}\, p_{hy}\, h_c\, t_b)$$

Resulting corner moments are designated M_{Bhye}, M_{Ihye}, M_{Dhye}, and M_{Fhye} for earth and M_{Bhyr}, M_{Ihyr}, M_{Dhyr}, and M_{Fhyr} for rock foundation analyses. Moments are in ft-lbs, h_c is in ft, t_t and t_b are in inches.

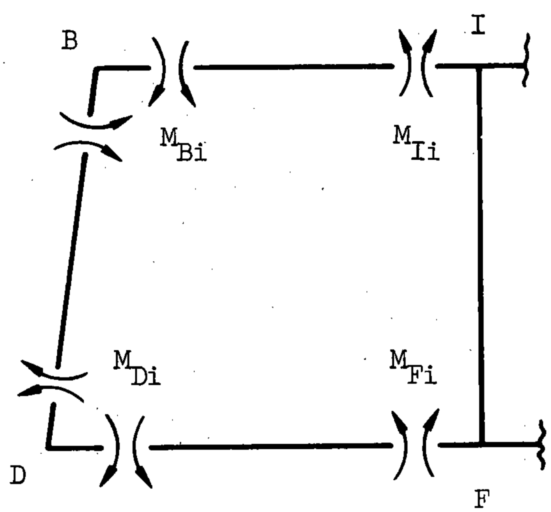

Figure 2-10. Positive moments from Slope Deflection solution.

Design Criteria

Materials
Class 4000 concrete and intermediate grade steel are assumed.

Working Stress Design
Design of sections is in accordance with working stress methods. The allowable stresses in psi are

Extreme fiber stress in flexure	$f_c = 1600$
Shear, V/bd at (d) from face of support*	$v = 70$
Flexural Bond	
tension top bars	$u = 3.4\sqrt{f_c'}/D$
other tension bars	$u = 4.8\sqrt{f_c'}/D$
Steel	
in tension	$f_s = 20{,}000$
in compression, axially loaded columns	$f_s = 16{,}000$

Minimum Slab Thicknesses

Top slab and sidewalls	10 inches
Bottom slab	11 inches

Sidewall Batter
Approximately 3/8 in. per foot, using whole inches for sidewall thicknesses at top and bottom of the sidewall.

Temperature and Shrinkage Steel
The minimum steel ratios are

for outside faces	$p_t = 0.001$
for inside faces	$p_t = 0.002$

Slabs more than 32 inches thick are taken as 32 inches.

Web Reinforcement
The necessity of providing some type of stirrup or tie in the slabs because of bending action is avoided by

(1) limiting the shear stress, as a measure of diagonal tension, so that web steel is not required, and

(2) providing sufficient effective depth of sections so that compression steel is not required for bending.

Cover for Reinforcement
Steel cover is everywhere 2 inches except for outside steel in the bottom slab where cover is 3 inches.

Spacing for Reinforcement
The maximum permissible spacing of any reinforcement is 18 inches.

*In some cases shear may be critical at the face of the support, see page 17 of TR-42.

Determination of Required Slab Thicknesses

The thickness of the centerwall is governed by direct compression. The thicknesses of all other slabs is governed by shear design or by the decision that compression steel shall not be required in bending. Slab end moments affect shear values in a member. Hence thicknesses required by shear are functions of the corner moments in the conduit. Indeterminate moment analysis depends on the thicknesses and span lengths of all members. Hence a convergence process is required in which cycles of shear design and moment analyses are repeated until a stable set of thicknesses is obtained. In each cycle, a set of required slab thicknesses, corresponding to a particular set of conduit corner moments, is computed.

Thicknesses Required by Shear

Since end moments on a member are in general unequal, the controlling thicknesses may be determined by shear at either end of the member. Table 2-1 lists the basic set or sets of loads and the external load

Table 2-1. Loadings for shear thickness design.

Slab	End Under Consideration	Earth Foundation		Rock Foundation	
		No Internal Water	With Internal Water	No Internal Water	With Internal Water
top slab	end I	B1-LC#1	B2-LC#1 or B3-LC#2	B1-LC#1	B2-LC#1 or B3-LC#5
top slab	end B	B1-LC#3	B1-LC#3 or B3-LC#0	B1-LC#6	B1-LC#6 or B3-LC#0
sidewall	end B	B1-LC#2	B1-LC-2 or B3-LC#1	B1-LC#6	B1-LC#6 or B3-LC#1
sidewall	end D	B1-LC#3	B1-LC#3 or B3-LC#0	B1-LC#3	B1-LC#3 or B3-LC#4
bottom slab	end D	B1-LC#3	B1-LC#3 or B3-LC#0	B1-LC#3	B1-LC#3 or B3-LC#4
bottom slab	end F	B1-LC#1	B2-LC#1 or B3-LC#2	B1-LC#1	B2-LC#1 or B3-LC#5

combinations for each design mode which must be considered to obtain the required thickness for shear for each slab. See page 8 of TR-42 for the definition of basic sets of loads. Critical shear is located a distance equal to the effective depth (d) from the face of the support when the loading is entirely external. When internal water loads are considered, critical shear may be located at the face of the support. The B3 loadings listed in Table 2-1 are the ones that may cause critical shear at the face of the support.

The shear design of each slab of a pressure conduit is performed in four parts corresponding to the two locations of critical shear at each end of the slab. Only the thickness of the concerned slab is considered a variable. The thicknesses obtained in the preceding cycle are used for the thicknesses of adjacent slabs and to compute span lengths.

The top slab is used to illustrate shear design. The following discussion assumes a pressure conduit founded on earth. Shear in the top slab depends on the dead weight of the slab. The dead weight depends on the thickness which is being determined. Hence a convergence process is desirable. Figure 2-11 shows the various loadings involved. Moments having positive Slope Deflection signs are assumed. Thus the sense of moment reactions is established. The largest of the four computed thicknesses controls.

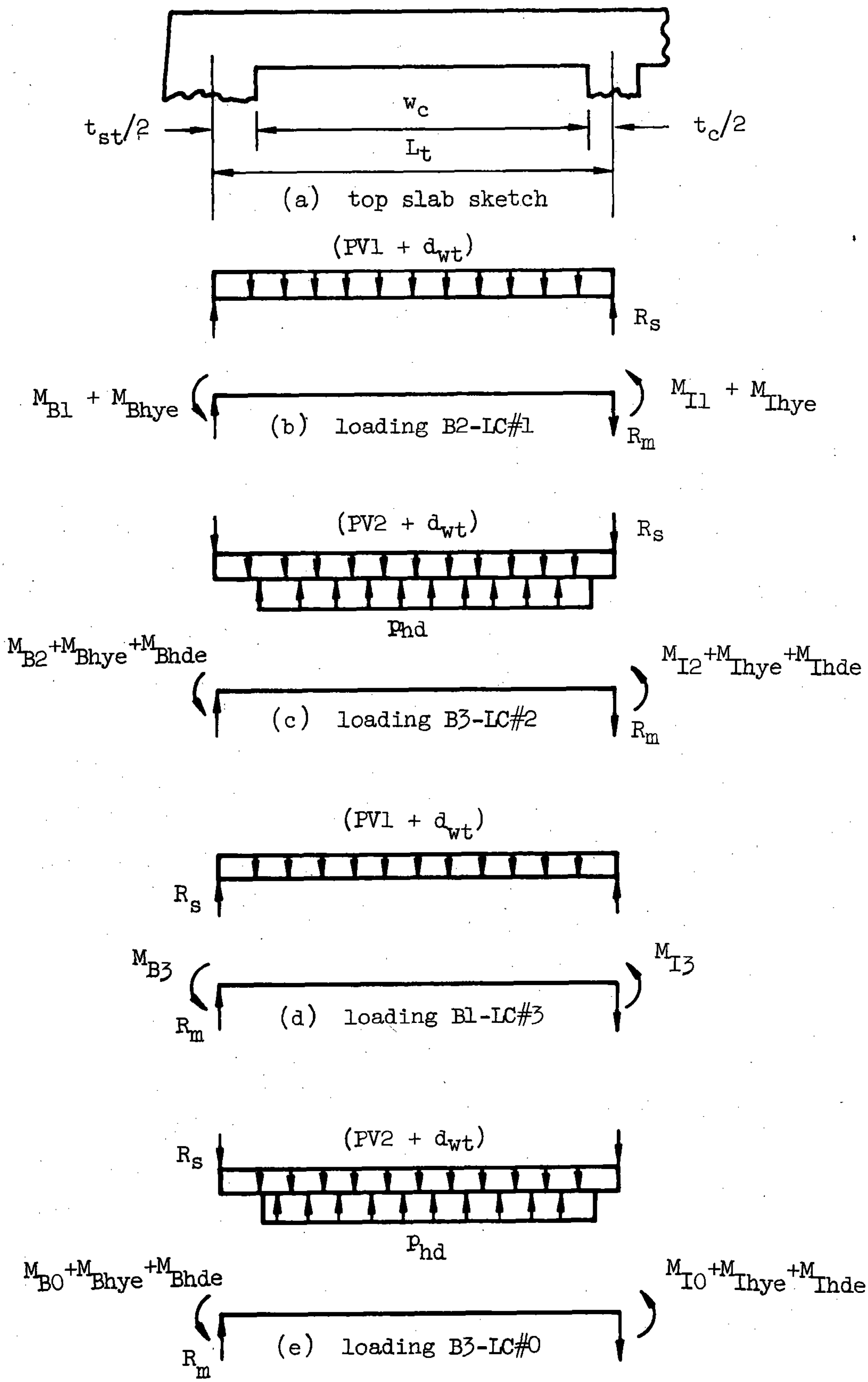

Figure 2-11. Loads for shear thickness design of top slab.

Thickness at I due to loading B2-LC#1. - From sketch (b) of Figure 2-11, the simple span reaction is

$$R_s = \frac{1}{2}(PV1 + d_{wt})L_t$$

where

$$d_{wt} = 150\ t_t/12$$

and

$$t_t = d + 2.5$$

The reaction due to end moments is

$$R_m = (M_{B1} + M_{I1} + M_{Bhye} + M_{Ihye})/L_t$$

Shear at distance (d) from the face at I, is

$$v = \frac{R_s - (PV1 + d_{wt})t_c/24 - R_m - (PV1 + d_{wt})d/12}{bd}$$

or, the required slab thickness is

$$t_t = \frac{R_s - (PV1 + d_{wt})t_c/24 - R_m}{840 + (PV1 + d_{wt})/12} + 2.5$$

In these relations, moments are in ft-lbs per ft, and

- $PV1$ = vertical unit load of LC#1, in psf
- d_{wt} = dead weight of top slab, in psf
- L_t = top span, in ft
- R_s = simple span reaction, in lbs per ft
- t_t = top slab thickness, in inches
- t_c = centerwall thickness, in inches
- R_m = reaction due to moments, in lbs per ft
- v = allowable shear stress = 70 psi
- b = 12 inches
- d = effective depth of top slab.

Thickness at I due to loading B3-LC#2. - From sketch (c) of Figure 2-11, the simple span reaction is

$$R_s = P_{hd}\ w_c(\frac{1}{2}\ w_c + t_{st}/24)/L_t - \frac{1}{2}(PV2 + d_{wt})L_t$$

The reaction due to end moments is

$$R_m = (M_{B2} + M_{I2} + M_{Bhye} + M_{Ihye} + M_{Bhde} + M_{Ihde})/L_t$$

Shear at the face of the support at I, is

$$v = \frac{R_s + (PV2 + d_{wt})t_c/24 + R_m}{bd}$$

or, the required slab thickness is

$$t_t = \frac{R_s + (PV2 + d_{wt})t_c/24 + R_m}{840} + 2.5$$

In these relations, in addition to those given previously

$PV2$ = vertical unit load of LC#2, in psf

w_c = clear width of one cell, in ft

$p_{hd} = \gamma_w h_w = 62.4 h_w$, in psf

$h_w = \frac{1}{2}(\frac{PV2}{100})$ = internal pressure head, in ft

t_{st} = thickness at top of sidewall, in inches

Thickness at B due to loading B1-LC#3. - From sketch (d) of Figure 2-11

$$R_s = \frac{1}{2}(PV1 + d_{wt})L_t$$

and

$$R_m = (M_{B3} + M_{I3})/L_t$$

The required slab thickness, with shear critical at distance (d) from the face at B, is

$$t_t = \frac{R_s - (PV1 + d_{wt})t_{st}/24 + R_m}{840 + (PV1 + d_{wt})/12} + 2.5$$

Thickness at B due to loading B3-LC#0. - From sketch (e) of Figure 2-11

$$R_s = p_{hd}\, w_c(\frac{1}{2} w_c + t_c/24)/L_t - \frac{1}{2}(PV2 + d_{wt})L_t$$

and

$$R_m = (M_{BO} + M_{IO} + M_{Bhye} + M_{Ihye} + M_{Bhde} + M_{Ihde})/L_t$$

The required slab thickness, with shear critical at the face of the support at B, is

$$t_t = \frac{R_s + (PV2 + d_{wt})t_{st}/24 - R_m}{840} + 2.5$$

Thickness design of sidewall and bottom slab. - Shear design of the sidewall proceeds in a similar manner to that shown above for the top slab, with two exceptions. First, shear in the sidewall does not depend on the dead weight of the sidewall, hence required thicknesses may be determined directly. Second, to account for trapezoidal external sidewall loads, an idealized shear curve, as discussed on pages 19 - 21 of TR-42, is used when the required effective depth at the top of the sidewall, due to external loads, is sufficiently large.

Shear design of the bottom slab is similar to that shown for the top slab except that shear in the bottom slab does not depend on the dead weight of the bottom slab. The bottom slab does carry the dead weight of the top slab, sidewall, and centerwall except for certain rock foundation computations.

Thickness of Centerwall
Due to vertical symmetry of both the loading on, and the shape of the conduit, the centerwall carries direct force only. The thickness of the centerwall is computed from the axial load equation

$$P = 0.85A_g(0.25f_c' + f_s p_g)$$

where

$A_g = bt_c = 12t_c$, in in^2 per ft

$f_c' = 4000$ psi

$f_s = 16000$ psi

p_g = steel ratio, taken as 0.01 per ACI 318-63 section 913(a)

P = axial load, in lbs per ft

t_c = thickness of centerwall, in inches

thus

$t_c = P/11832$

however t_c is made at least equal to t_{st} or 12 inches, whichever is smaller.

The maximum compressive axial load is computed from B1-LC#1 if internal water loads are not included in the design or from B2-LC#1 if internal water loads are included. The axial load in the centerwall is twice the reaction at F in the bottom slab span DF, or for loading B2-LC#1

$$P = 2(R_s + R_m)$$

where

$R_s = \frac{1}{2}(PV1 + d_{wb})L_b$, in lbs per ft

$R_m = (M_{D1} + M_{F1} + M_{Dhye} + M_{Fhye})/L_b$, in lbs per ft

Steel Area Required at Critical Locations

After slab thicknesses and corner moments for external and internal loads have been determined, steel areas required at the twenty locations shown in Figure 1-1 are computed. The procedure for determining required steel area for any acceptable combination of moment and direct force is given on pages 31 - 34 of TR-42. Incrementing a slab thickness, to avoid the use of compression steel in bending, may disturb the balance between shear stress and moments previously attained. Thus, if incrementing occurs, some sections may be slightly overstressed in shear.

Maximum Moment Plus Associated Direct Force
Table 2-2 lists the external load combinations which may give maximum required steel areas at interior locations in the top slab, sidewall, and bottom slab. In the case of positive interior steel, the section of maximum positive bending moment is unknown. This section is located, the moment and direct force are evaluated, and the steel area is determined and recorded for the midspan location. The negative interior steel area determined is that actually required at the midspan location.

For pressure conduits all three basic sets of loads are investigated to determine the one producing the maximum required steel area at each location. All three are investigated because it is impossible to always correctly predetermine which basic set governs.

Table 2-2. External load combinations for interior moments.

Location (See Figure 1-1)	Earth Foundation	Rock Foundation
3 4	LC#1 LC#2	LC#1 LC#5
9 10	LC#2 LC#1	LC#5 LC#1
15 16	LC#1 LC#2	LC#1 LC#5

Table 2-3 lists the external load combinations which are investigated to obtain the maximum required steel areas at the faces of supports in the top slab, sidewall, and bottom slab. Two or three load combinations are given for each location. These load combinations are given because maximum required area may be caused by either the load combination producing maximum corner moment, an alternate load combination which produces a smaller moment but requires a greater steel area because of a smaller direct force, or a load combination that does not produce maximum corner moment but may produce maximum moment at the support face.

For pressure conduits all three basic sets of loads are investigated in conjunction with each of the listed external load combinations to determine the particular loading producing the maximum required steel area.

Table 2-3. External load combinations for moments at faces of supports.

Location (See Figure 1-1)	Earth Foundation	Rock Foundation
1	LC#1, LC#2, LC#3	LC#4, LC#5, LC#6
2	LC#0, LC#1	LC#0, LC#1
5	LC#0, LC#1	LC#0, LC#1
6	LC#1, LC#2, LC#3	LC#4, LC#5, LC#6
7	LC#0, LC#2	LC#0, LC#2
8	LC#1, LC#2, LC#3	LC#4, LC#5, LC#6
11	LC#0, LC#2	LC#4, LC#5, LC#6
12	LC#1, LC#2, LC#3	LC#1, LC#2, LC#3
13	LC#0, LC#1	LC#1, LC#4
14	LC#1, LC#2, LC#3	LC#1, LC#3, LC#5
17	LC#1, LC#2, LC#3	LC#1, LC#3, LC#5
18	LC#0, LC#1	LC#1, LC#4

Maximum Direct Force Plus Associated Moment

Occasionally the maximum required steel area at a section is governed by the maximum direct force plus associated moment rather than maximum moment plus associated direct force. Table 2-4 lists the basic set of loads and external load combinations producing these maximum direct forces in the top slab, sidewall, and bottom slab. As shown in the table, the bottom slab may carry direct tension even though the conduit does not carry internal water, if the conduit is founded on rock.

Procedure at a Section

With the corner moments known, the design moment and direct force at a given section may be computed by statics for each of the loadings that is considered. This is illustrated below for three top slab locations and loadings. All end moments are assumed with positive Slope Deflection signs so that senses are automatically established and relations are algebraically consistent. With the moment and direct force at a section known, the required steel area can be determined.

In the following illustrations, moments are in ft-lbs per ft, direct forces are in lbs per ft, pressures are in psf, thicknesses are in inches, and distances are in ft.

Table 2-4. Loadings for maximum direct forces.

Member	Compression	Tension
Top Slab	On earth B1-LC#2 On rock B1-LC#6	B3-LC#0
Sidewall	B1-LC#3	B3-LC#0
Bottom Slab	B1-LC#3	On earth B3-LC#0 On rock B3-LC#4 On rock B1-LC#4

<u>Location 3 - positive bending with loading B2-LC#1.</u> - This case includes internal hydrostatic sidewall loading due to the conduit flowing full as an open channel. The section of maximum moment is unknown.

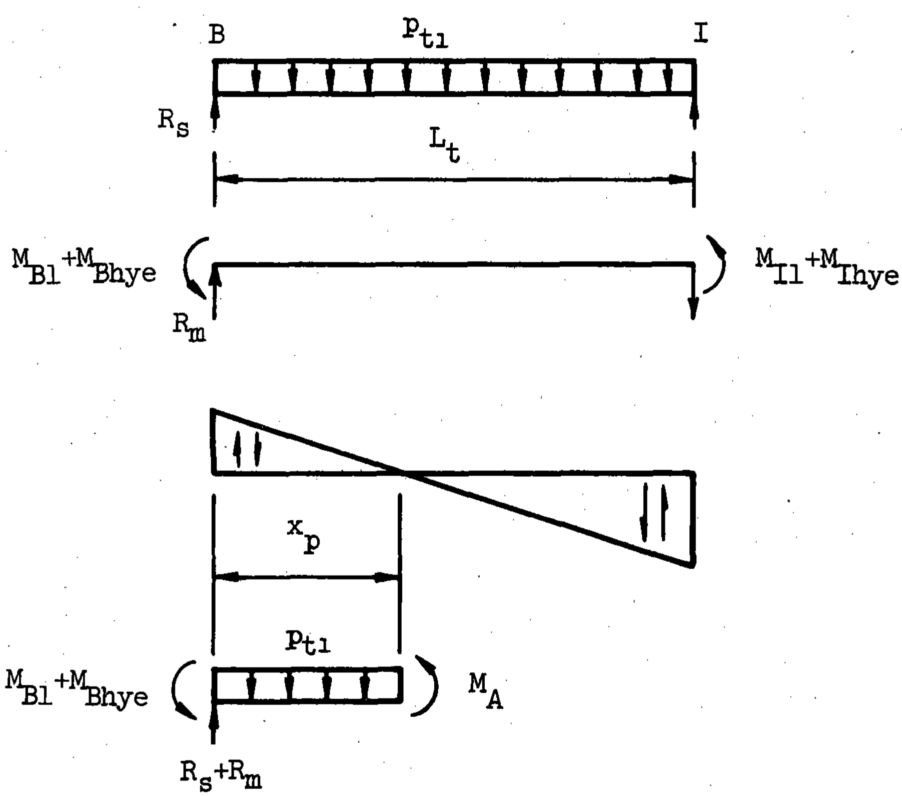

Figure 2-12. Positive bending in top slab with loading B2-LC#1.

From Figure 2-12, the simple span reaction at B is

$$R_s = \frac{1}{2} p_{t1} L_t$$

The reaction due to end moments is

$$R_m = (M_{Bl} + M_{Il} + M_{Bhye} + M_{Ihye})/L_t$$

The shear at distance x_p from the left support is

$$V_p = R_s + R_m - p_{t1} x_p$$

The section of maximum positive moment is determined by setting $V_p = 0$ and solving for x_p. Thus

$$x_p = \frac{R_s + R_m}{p_{t1}}$$

If $x_p < t_{st}/24$, take $x_p = t_{st}/24$.

If $x_p > (L_t - t_c/24,)$ take $x_p = (L_t - t_c/24)$.

Letting M_A be the desired moment

$$M_A = (R_s + R_m)x_p - \frac{1}{2} p_{t1} x_p^2 - (M_{Bl} + M_{Bhye})$$

If, as written, $M_A < 0$ the desired moment does not exist. The associated direct force in the top slab may be obtained as the sum of four components, see pages 39 - 40 and Figure 27 of TR-42. Hence

$$N_t = p_{s1}(L_s/3 + t_t/24) - (\frac{1}{2} p_{hy} h_c)(h_c/3 + t_b/24)/L_s$$
$$+(M_{Bl} + M_{Dl} + M_{Bhye} + M_{Dhye})/L_s$$

Location 4 - negative bending with loading B3-LC#5. - This case includes internal water loads due to the conduit flowing full as a pressure conduit. The midspan section is a distance x_{mid} from the left support, where

$$x_{mid} = w_c/2 + t_{st}/24$$

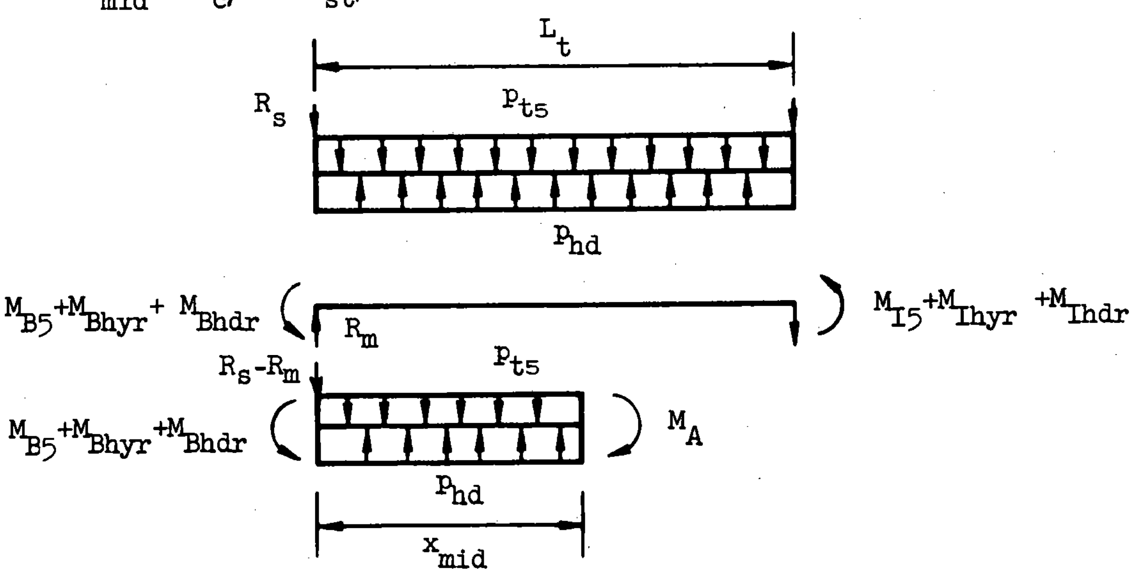

Figure 2-13. Negative bending in top slab with loading B3-LC#5.

From Figure 2-13

$$R_s = \frac{1}{2}(p_{hd} - p_{t5})L_t$$

and

$$R_m = (M_{B5} + M_{I5} + M_{Bhyr} + M_{Ihyr} + M_{Bhdr} + M_{Ihdr})/L_t$$

Again letting M_A be the desired moment

$$M_A = (R_s - R_m)x_{mid} - \frac{1}{2}(p_{hd} - p_{t5})x^2_{mid} + (M_{B5} + M_{Bhyr} + M_{Bhdr})$$

If, as written, $M_A < 0$ the desired moment does not exist. The associated direct force in the top slab includes components due to external lateral loading, internal hydrostatic sidewall loading, and internal pressure head loading. The direct force is

$$N_t = p_{s5}(L_s/2 + t_t/24) - (\frac{1}{2}\, p_{hy}\, h_c)(h_c/3 + t_b/24)/L_s$$

$$- p_{hd}\, L_s/2 + (M_{B5} + M_{D5} + M_{Bhyr} + M_{Dhyr} + M_{Bhdr} + M_{Dhdr})/L_s$$

Since the goal here is to obtain maximum negative bending at location 4, the external lateral load is assumed uniformly distributed. Thus no adjustment for a trapezoidal distribution is made in the direct force.

<u>Location 6 - negative bending with loading B1-LC#3.</u> - Location 4 in the single cell conduits of TR-42 corresponds to location 6 in the twin cell conduits of this technical release. In TR-42 advantage is

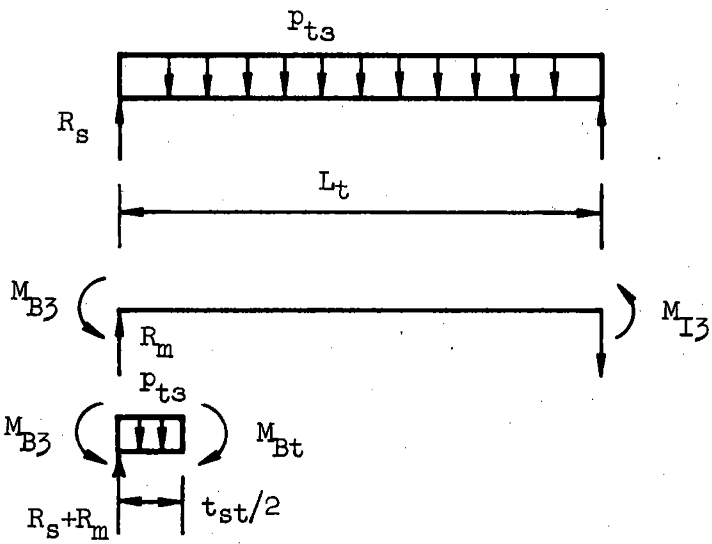

Figure 2-14. Negative bending in top slab with loading B1-LC#3

taken of symmetry of the moment diagram, here a more general approach is required.

$$R_s = \frac{1}{2}\, p_{t3}\, L_t$$

$$R_m = (M_{B3} + M_{I3})/L_t$$

Letting M_{Bt} be the desired moment

$$M_{Bt} = M_{B3} - (R_s + R_m)t_{st}/24 + \frac{1}{2} p_{t3}(t_{st}/24)^2$$

If, as written, $M_{Bt} < 0$ the desired moment does not exist. The associated direct force in the top slab may be obtained as the sum of three components, see page 38 and Figure 24 of TR-42. Hence

$$N_t = p_{s3}(L_s/2 + t_t/24) + (M_{B3} + M_{D3})/L_s$$

Centerwall Steel

As previously given, the maximum compressive axial force in the centerwall occurs with loading B1-LC#1 if there are no internal water loads and with B2-LC#1 if internal water loads are included. For loading B2-LC#1, the compressive force is

$$P = 2(R_s + R_m)$$

where, again

$$R_s = \frac{1}{2} p_{b1} L_b$$

$$R_m = (M_{D1} + M_{F1} + M_{Dhye} + M_{Fhye})/L_b$$

The axial load formula is solved for required steel area. One half of this area is provided in each face. Thus

$$A_s = \frac{1}{2}\left\{ \frac{1}{16000}(P/0.85 - 12000t_c) \right\}$$

where

A_s = vertical steel in each face of centerwall, in sq. in per ft

P = axial compression, in lbs per ft

t_c = centerwall thickness, in inches

Maximum tensile axial force occurs in the centerwall, if it occurs, with one of four loadisng. These are B3-LC#2 or B1-LC#2 if the conduit is founded on earth and B3-LC#5 or B1-LC#5 if founded on rock. Both corresponding B3 and B1 loadings are investigated. The B3 loading will not require a greater area than the B1 loading unless the internal pressure head is sufficient to overcome the compressive force in the centerwall caused by the internal hydrostatic sidewall loading. The axial force in the centerwall is twice the reaction at I in the top slab span BI. The top joint I is used rather than the bottom joint F to avoid the necessity of computing the value of the concentrated reaction at F for conduits founded on rock. Figure 2-15 shows the assumed senses for loading B3-LC#2.

The reactions are

$$R_s = \frac{1}{2}(p_{hd} - p_{t2})L_t$$

$$R_m = (M_{B2} + M_{I2} + M_{Bhye} + M_{Ihye} + M_{Bhde} + M_{Ihde})/L_t$$

Thus

$$P = 2(R_s + R_m)$$

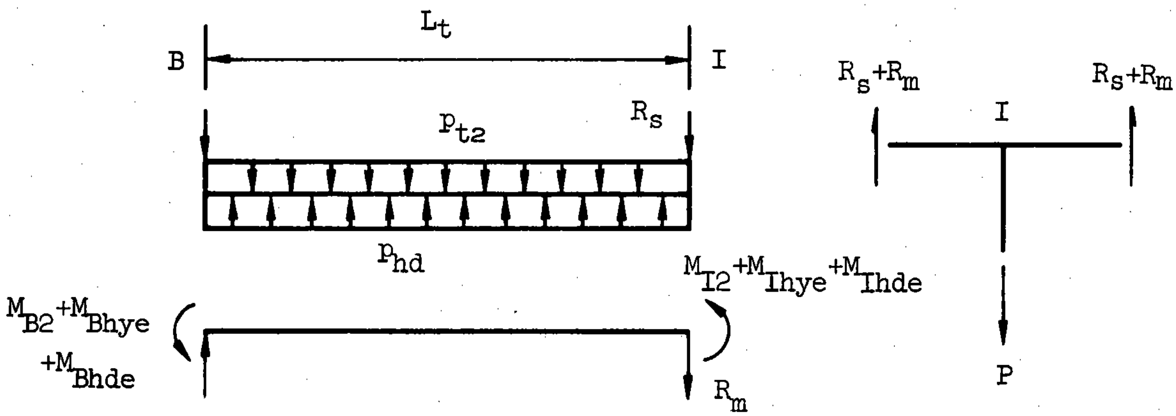

Figure 2-15. Centerwall tension for loading B3-LC#2

If, as written, $P < 0$ axial tension does not exist in the centerwall. One-half of the required area is provided in each face, or in sq. in. per ft

$$A_s = \frac{1}{2}\left(\frac{P}{20000}\right)$$

The larger required area, for compressive or tensile axial force, governs.

Anchorage of Positive Steel

The discussion on pages 43 - 45 of TR-42 concerning anchorage of positive steel in essence also applies to twin cell conduits. The inside steel at the joints of the conduit, including the centerwall steel, must be provided sufficient anchorage whenever tension exists in the bar under some combination of loads.

It is not necessary that separate analyses be performed to establish whether the positive steel at the face of the support at locations 1, 5, 7, 11, 13, and 17 is ever in tension. The determinations are made and results recorded for anchorage locations 1 through 6 at the time the required area is determined. Similarly, if the centerwall is ever in tension, this fact is recorded for anchorage locations 7 and 8.

Tension may occur in the inside steel at the corner diagonals at B and D even though it is possible tension never occurs in the corresponding steel at the support face. This is investigated as shown in TR-42 except that the moments due to internal water loads should carry the subscripts e or r to differentiate between analyses based on earth or rock foundations.

Spacing Required by Flexural Bond

Flexural bond stresses must be held within tolerable values whenever a bar is in tension. Thus the maximum shear that can exist at a section, when the associated steel at the section is acting in tension, must be determined. As shown on page 47 of TR-42, allowable bar spacing is independent of bar size, for usual sizes, and is given by

$$s = 7{,}093(d/V)$$

for tension top bars, and

$$s = 10{,}015(d/V)$$

for other tension bars, where

s = center to center spacing of bars, in inches
d = effective depth at the section, in inches
V = shear at the section, in lbs per ft

Load Combinations Producing Minimum Required Spacing

Flexural bond allowable steel spacing at a particular location is computed only after it is determined the tensile area required in bending for that location is greater than zero. Table 2-5 lists the external load combinations that produce maximum shear at interior locations when the steel at that location is acting in tension. This table is the same as Table 2-2 with the exception of additional load combinations to be considered at location 10. In the case of positive interior steel

Table 2-5. External load combinations for flexural bond at interior locations.

Location (See Figure 1-1)	Earth Foundation	Rock Foundation
3	LC#1	LC#1
4	LC#2	LC#5
9	LC#2	LC#5
10	LC#0, LC#1	LC#0, LC#1, LC#4
15	LC#1	LC#1
16	LC#2	LC#5

the points of inflection are located, the shear at the points of inflection is evaluated, and the steel spacing is determined and recorded for the midspan location. The negative interior steel spacing determined is that actually required at the midspan location. For pressure conduits all three basic sets of loads are considered to determine the one producing the minimum allowable spacing at each location. Only the basic sets of loads that produce tension in the concerned steel are involved in determining the controlling spacing.

In connection with location 10, the additional load combinations require explanation. LC#1 will produce the greatest requirement for negative steel area. However, LC#0 or LC#4, if either produces tension in the negative steel, may require a smaller steel spacing than LC#1.

Table 2-6 lists the external load combinations that may produce maximum shear at the faces of supports when the steel at that location is acting in tension. Two or three load combinations are given for each location. The only load combinations investigated are those producing tension in the concerned steel. For pressure conduits all three basic sets of loads are investigated.

Table 2-6. External load combinations for flexural bond at faces of supports.

Location (See Figure 1-1)	Earth Foundation	Rock Foundation
1	LC#1, LC#2, LC#3	LC#1, LC#3, LC#5
2	LC#0, LC#1	LC#0, LC#1
5	LC#0, LC#1	LC#0, LC#1
6	LC#1, LC#2, LC#3	LC#4, LC#5, LC#6
7	LC#1, LC#2	LC#1, LC#2
8	LC#1, LC#2, LC#3	LC#4, LC#5, LC#6
11	LC#0, LC#2	LC#2, LC#4, LC#6
12	LC#1, LC#2, LC#3	LC#1, LC#2, LC#3
13	LC#0, LC#1	LC#1, LC#4
14	LC#1, LC#2, LC#3	LC#1, LC#2, LC#3
17	LC#1, LC#2, LC#3	LC#1, LC#3, LC#5
18	LC#0, LC#1	LC#0, LC#1

Procedure at a Section

Representative computations of steel spacing for flexural bond are illustrated below for three top slab locations and loadings. Many similar computations are made depending on the loadings that produce tension in the steel at the location under consideration.

Location 3 - spacing with loading B3-LC#1. - If tension occurs in the top slab positive steel for this loading, the location of the section, and the magnitude of the maximum positive bending moment have been determined. Let these be x_p and M_A respectively.

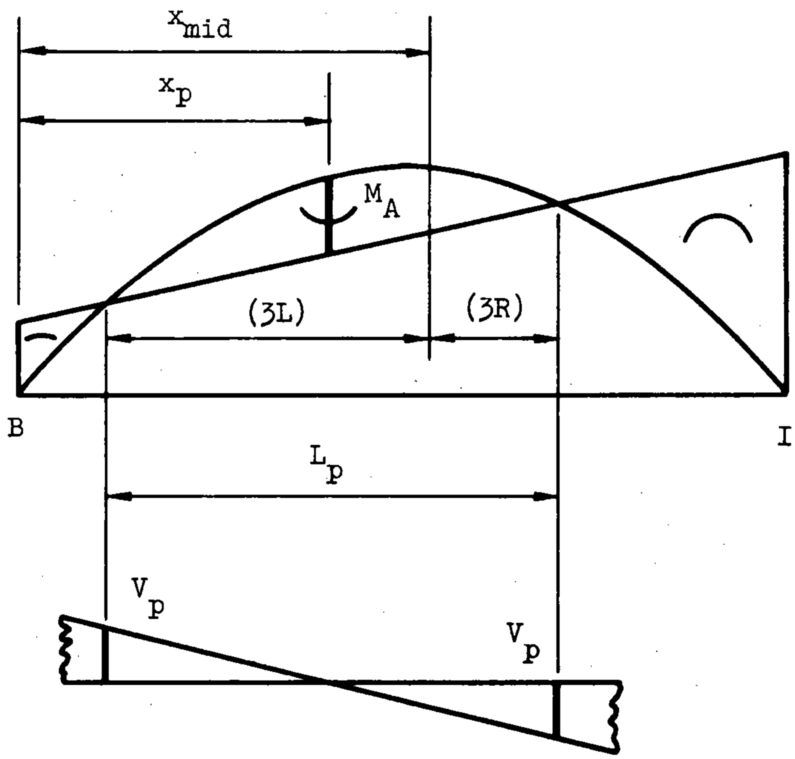

Figure 2-16. Points of inflection in top slab with loading B3-LC#1

Referring to Figure 2-16, the span, in ft, between points of inflection is

$$L_p = (8M_A/(p_{t1} - p_{hd}))^{1/2}$$

and the shear at the points of inflection is

$$V_p = (p_{t1} - p_{hd})L_p/2$$

so the required spacing at the points of inflection, in inches, is

$$s = 10{,}015\ d_t/V_p$$

where d_t is the effective depth of the top slab.

The positions of the left and right points of inflection measured from midspan location 3 are given, in ft, by

$$(3L) = x_{mid} - (x_p - L_p/2)$$

$$(3R) = (x_p + L_p/2) - x_{mid}$$

in which

$$x_{mid} = w_c/2 + t_{st}/24$$

where distances are in ft and thickness is in inches.

Location 4 - spacing with loading B2-LC#5. - Ordinarily this loading does not control the minimum spacing. If this loading produces tension in the negative steel, then by reasoning similar to that in connection with Figures 2-12 and 2-13,

$$R_s = \frac{1}{2} p_{t5} L_t$$

$$R_m = (M_{B5} + M_{I5} + M_{Bhyr} + M_{Ihyr} + M_{Bhdr} + M_{Ihdr})/L_t$$

The shear at midspan location 4 is

$$V_{mid} = \left| (R_s + R_m) - p_{t5} x_{mid} \right|$$

If the depth below the negative steel exceeds twelve inches, the required spacing is

$$s = 7{,}093\ d_t/V_{mid}$$

otherwise

$$s = 10{,}015\ d_t/V_{mid}$$

Location 6 - spacing with loading B1-LC#3. - This loading will usually control the minimum spacing for conduits founded on earth. From Figure 2-14

$$R_s = \frac{1}{2} p_{t3} L_t$$

$$R_m = (M_{B3} + M_{I3})/L_t$$

The shear at the face of the support is

$$V_f = (R_s + R_m) - p_{t3}\ t_{st}/24$$

The depth below the negative steel is checked to determine whether the steel qualifies as tension top bars or as other tension bars. Allowable spacing is computed accordingly.

Summary of Design

Figure 2-17 presents a summary flow chart showing the sequence of the design process discussed on the preceding pages. The basic logic of the computer program prepared to obtain cross section designs of twin cell rectangular conduits parallels this flow chart.

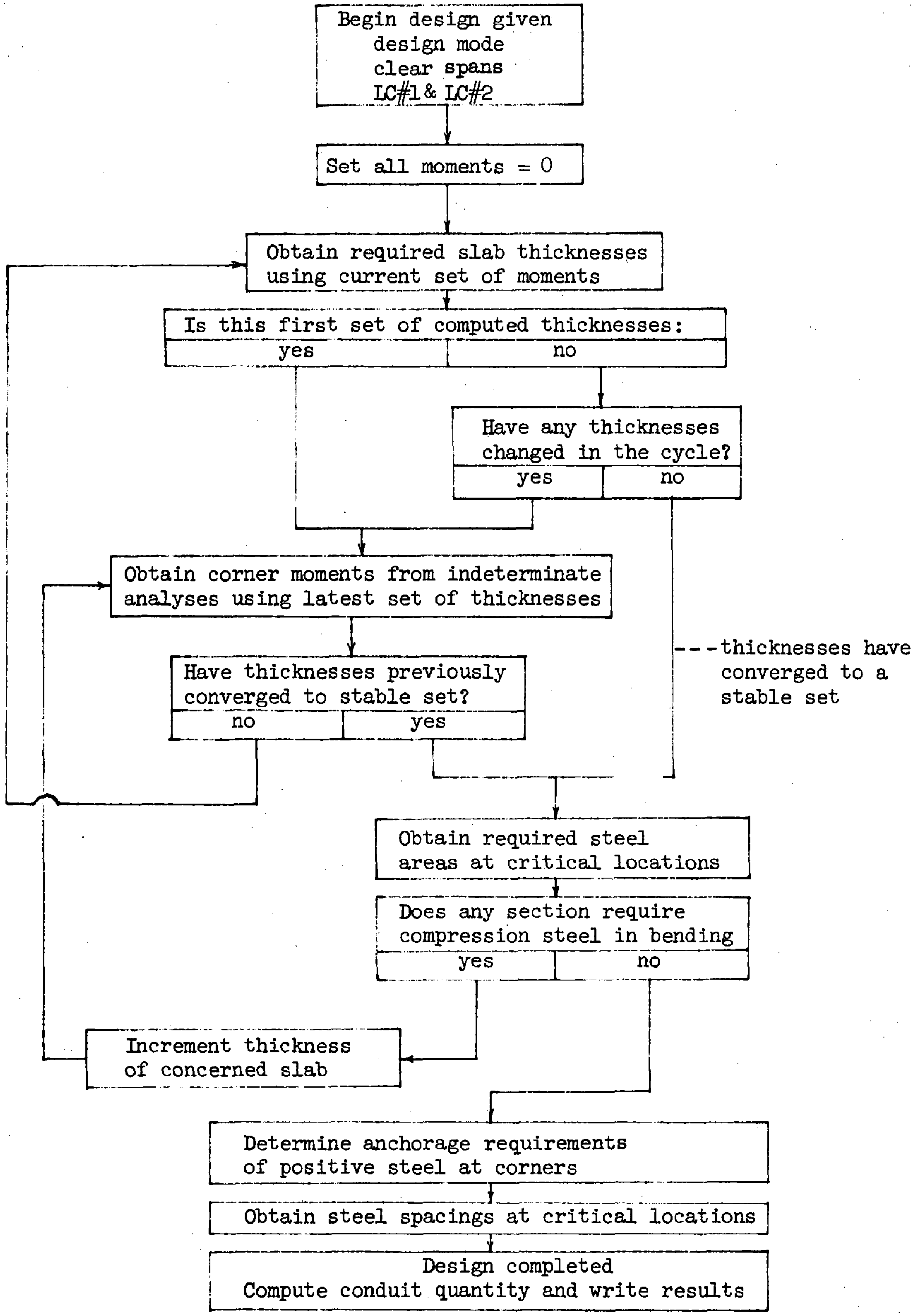

Figure 2-17. Summary flow chart of design process.

TWIN CELL RECTANGULAR CONDUIT
CROSS SECTION DESIGN
ELASTIC ANALYSIS AND WORKING STRESS DESIGN ARE USED

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR

EXAMPLE SPECIAL DESIGNS FOR TWIN CELL TECHNICAL RELEASE.
JOAN FOR ESA ---- 5/19/70

SPECIAL DESIGN NO. 15-TW DESIGN MODE=11

CLEAR SPANS ARE 6.00 HIGH AND 4.00 WIDE

LOAD PARAMETERS ARE
PV1= 4000. PH1= 1000. PV2 = 2000. PH2= 3000.

NUMBER OF CYCLES REQUIRED FOR CONVERGENCE= 4
NUMBER OF TRIAL DESIGNS MADE = 1

REQUIRED SLAB THICKNESSES ARE
TTOP=12.00 TSTOP =11.00 TSBOT=15.00 TBOT=13.00 TCTR=11.00

CONDUIT QUANTITY = 1.5404 CU.YDS.PER FT.

REQUIRED STEEL AREA	MAXIMUM STEEL SPACING
A(1)= 0.29	S(1)= 18.00
A(2)= 0.57	S(2)= 9.09
A(3)= 0.29	S(3)= 16.38
A(4)= 0.14	S(4)= 18.00
A(5)= 0.29	S(5)= 14.97
A(5)= 0.27	S(6)= 9.77
A(7)= 0.27	S(7)= 18.00
A(8)= 0.28	S(8)= 9.29
A(9)= 0.30	S(9)= 15.95
A(10)= 0.15	S(10)= 18.00
A(11)= 0.35	S(11)= 18.00
A(12)= 0.25	S(12)= 12.46
A(13)= 0.31	S(13)= 18.00
A(14)= 0.31	S(14)= 9.31
A(15)= 0.31	S(15)= 16.41
A(16)= 0.16	S(16)= 18.00
A(17)= 0.31	S(17)= 18.00
A(18)= 0.42	S(18)= 9.03
A(19)= 0.26	S(19)= 18.00
A(20)= 0.26	S(20)= 18.00

POINTS OF INFLECTION ARE

3L = 1.92	3R= 0.88
9L = 2.19	9R= 2.07
15L= 1.82	15R= 1.07

POSITIVE ANCHORAGE REQUIREMENT = 02005600

****** END OF DESIGN ******

TWIN CELL RECTANGULAR CONDUIT
CROSS SECTION DESIGN
ELASTIC ANALYSIS AND WORKING STRESS DESIGN ARE USED

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR

EXAMPLE SPECIAL DESIGNS FOR TWIN CELL TECHNICAL RELEASE.
JOAN FOR ESA ---- 5/19/70

SPECIAL DESIGN NO. 16-TW DESIGN MODE=11

CLEAR SPANS ARE 4.00 HIGH AND 8.00 WIDE

LOAD PARAMETERS ARE
PV1=20000. PH1= 0. PV2=10000. PH2=10000.

NUMBER OF CYCLES REQUIRED FOR CONVERGENCE=11
NUMBER OF TRIAL DESIGNS MADE = 1

REQUIRED SLAB THICKNESSES ARE
TTOP=47.00 TSTOP=53.00 TSBOT=58.00 TBOT=48.00 TCTR=23.00

DESIGN DELETED, SEE MESSAGE NO. 3

****** END OF DESIGN ******

TWIN CELL RECTANGULAR CONDUIT
CROSS SECTION DESIGN
ELASTIC ANALYSIS AND WORKING STRESS DESIGN ARE USED

SPECIAL DESIGN PREPARED BY THE DESIGN UNIT AT HYATTSVILLE, MD.
FOR

EXAMPLE SPECIAL DESIGNS FOR TWIN CELL TECHNICAL RELEASE.
JOAN FOR ESA ---- 5/19/70

SPECIAL DESIGN NO. 17-TW DESIGN MODE=11

CLEAR SPANS ARE 7.00 HIGH AND 9.00 WIDE

LOAD PARAMETERS ARE
PV1=25500. PH1= 3750. PV2=13900. PH2=11200.

NUMBER OF CYCLES REQUIRED FOR CONVERGENCE= 5
NUMBER OF TRIAL DESIGNS MADE = 1

REQUIRED SLAB THICKNESSES ARE

TTOP=57.00	TSTOP=33.00	TSBOT=40.00	TBOT=57.00	TCTR=34.00
57.00	33.00	40.00	57.00	34.00

DESIGN DELETED, SEE MESSAGE NO. 5

****** END OF DESIGN ******